ON THE PERFORMANCE OF REAL-TIME NETWORK-BASED GNSS POSITIONING

Constantin-Octavian ANDREI[1], Lecturer PhD. Eng., Department of Survey Engineering, Chulalongkorn University, Bangkok, Thailand, Octavian.A@chula.ac.th
Mihaela CARDEI, PhD. Eng., Faculty of Hydrotechnics, Geodesy and Environmental Engineering Technical University "Gh. Asachi", Iasi, Romania.

Abstract: *Network-based Real Time Kinematic (NRTK) GNSS positioning has become a very common practice to many professional communities that require high accuracy positioning information in a cost-effective manner. NRTK takes advantage of the increased numbered of Continuous Operating Reference Stations (CORSs) deployed over a wide geographic region. Using raw GNSS measurements from a network of CORS stations, NRTK constructs network wide models that mitigates more reliable the distance dependent errors compared to single-base RTK GNSS positioning. As a result, NRTK allows users smooth transitions from the errors of one reference station to another.*

This study reports preliminary testing results of an investigation of the NRTK GNSS positioning from the user's point of view using ROMPOS service. First, the paper reviews different NRTK concepts. Then, several static tests are carried out to analyze the performance of NRTK positioning regarding the precision, accuracy and occupation time on both horizontal and vertical directions. In addition, the study illustrates the benefit of averaging the observations over a window of 1-3 minutes and re-occupying the points after 10-30 minutes later. The results demonstrate that NRTK is superior to single-base RTK and may be an economic alternative to establish control points of a certain accuracy requirements.

Keywords: *GNSS, PPP, CORS, Network-RTK, precision, accuracy.*

1. INTRODUCTION

Network-based Real-Time Kinematic (NRTK) positioning has become nowadays a very common tool for both scientific and professional world to obtained precise positioning information. Since its appearance, over a decade ago, the number of applications adopting this type of precise positioning has been expanded from the engineering surveying to GIS mapping, automated monitoring, machine control guidance, precision agriculture, vehicle fleet and asset management, airborne navigation, etc. The expansion has also been generated by the increased number of networks of Continuous Operating Reference Stations (CORSs) over large geographical areas. These networks offer real-time services, mitigate the distance-dependent errors between the reference station and rover receivers, and provide centimeter level positioning accuracy for longer distances comparing to the conventional RTK positioning.

In the conventional RTK positioning, a single *reference* station receiver makes observations and sends raw datato a stationary or moving *rover* receiver via a data radio link (UHF or VHF). The rover needs to work within a short distance from the reference station to exploit the spatial correlation property of various errors affecting satellite signal propagation.

---

[1] School of Engineering, Aalto University, Finland

However, spatial correlated errors can be effectively cancelled out only when the baseline vector between the reference and rover is limited to a distance of up to 10-20 km. In addition, the use of only single station poses certain risks to the user in case the reference station experiences any malfunctioning. Furthermore, the conventional RTK requires increased resources, such as equipment, labor, time, and financial costs. These constraints can be removed by using NRTK as a cost-effective manner to obtain precise positioning information.

In the following, the principles of Network RTK are first discussed together with benefits and drawbacks of the method (Section 2). Next, the current NRTK implementations (Section 3) are described from the algorithm point of view. The numerical results from various field tests and the corresponding analysis are shown and presented (Section 4). The conclusions are reported in the last section (Section 5).

2. NETWORK RTK PRINCIPLES

The aim of the reference network is to model and estimate the error sources, caused by ionosphere and troposphere, and satellite orbit errors, based on dual-frequency carrier phase measurements of a local or regional network of reference stations.

The main goal of NRTK is to model and minimize the influence of the distance-dependent errors on the rover computed positions within the network area. These errors are mainly caused by ionosphere, troposphere, and satellite orbits, and may be categorized in two groups: dispersive and non-dispersive (Brown and Keenan, 2005).

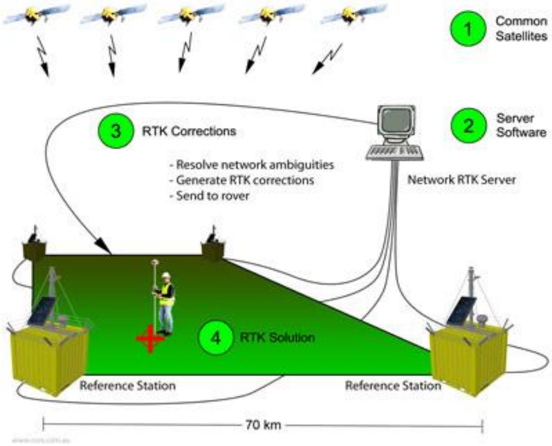


Fig. 1 – Principle of Network-based Real-Time Kinematic (NRTK) positioning

In principle, the NRTK approach consists of four main steps (Fig). In the first step, satellite observations are collected at the reference stations and transmitted to the network control and processing center. In the second step, the processing center resolves network ambiguities using an appropriate ambiguity resolution algorithm, and generates network corrections using one of the processing algorithms explained in Section 3. In the third step, the server transmits these corrections to the rover using various communication links and transmission protocols. In the last step, the rover computes RTK solution by combining own observation data with received network corrections.

There are several benefits to the user of using NRTK over single-base RTK positioning. A first benefit, there is no need to set-up a base station each time, thus no security issues, no lost time setting up, no worries to breaking down the base station equipment and radio. As a result, the overall cost and labor are reduced while mobility and efficiency are increased. A second benefit, the accuracy of the computed rover positions is more robust, homogeneous and consistent. The network processing software models the errors over the entire network area using the same datum and the same functional and stochastic models for GNSS network error modeling. A third benefit, the same area can be covered with fewer reference stations compared to the number required using single-based RTK. The intra-station distances between reference stations can be extended to up to 100 km. A forth benefit, NRTK increases reliability and availability of RTK corrections. Even though one reference station suffers of malfunctioning, a solution can still be obtained from the rest of the reference stations. A last benefit, NRTK approach supports multiple users and applications in a continuous manner 365/24/7.

Despite all these benefits, one can also identify several drawbacks, such as network subscription fees with a NRTK provider, limited wireless data access, dependence on an external source, interpolation or extrapolation issues when working outside the network envelope, and datum inconsistency with the user's required datum.

3. NETWORK RTK ALGORITMS

Currently, several NRTKcommercial implementations can be identified, such asthe Virtual Reference Station (VRS), Pseudo-Reference Station (PRS), individualized Master Auxiliary corrections (i-MAX), Area Correction Parameter (FKP), and the Master Auxiliary Concept (MAC). All approaches assume that a user calculates a double difference baseline between one reference station and rover. In VRS and PRS, referencing is made to a non-physical reference station located in the vicinity of the location of the rover and uses virtual observations generated to refer to this non-physical reference station. With these methods, the CPF computes corrections optimized for the position of the rover. The rover has no information about the size of the errors and their behavior. Conversely, FKP and MAX broadcast raw reference station observations and network information separately. The rover has the flexibility to control and perform positioning calculations. In this section, the most common NRTK algorithms are briefly discussed.

Area Correction Parameter (FKP)

The Flächen-Korrektur Parameter (FKP) or Area Correction Parametermethod is the oldest NRTK method and was developed in the mid 1990s(Wübenna et al., 1996).

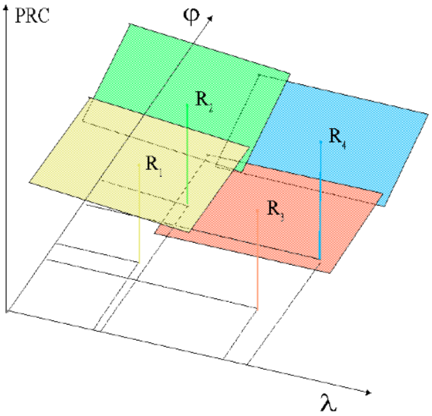


Fig. 2 – Area Correction Parameter concept(Wübenna et al., 1996)

The FKP method represents network information by estimating network coefficients of a surface centred at the location of a physical reference station (Wübbena and Bagge 2006). The coefficients are computed for each satellite covering ionospheric, tropospheric and orbit effects for a specific area as north-south and east-west gradients, at certain time intervals (at least every 10 sec). The network corrections and uncorrected raw observations from the master reference station are broadcast separately in RTCM formats. The corrections are transmitted in a special format (RTCM 2.3 message type 59), which requires changes of rover receiver hardware of additional hardware to convert the non-standard format to a standard RTCM data stream before used by the rover (Landau et al., 2002). In RTCM 3.1, FKP corrections can be sent via message types 1034 and 1035 for GPS and GLONASS observations, respectively. Once received, the rover may interpolate the messages to correct master reference station data, or convert the data into VRS corrections, or apply Precise Point Positioning (PPP), in what is known as PPP-RTK (Teunissen et al., 2010).

The basic advantages of the FKP implementation are that it requires only unidirectional communication link, no restriction on the number of users, and low load on network server because no complex models or creation of individual VRS are required. On the other hand, FKP implementation has its limitations, including the need of the rover to perform interpolation of measurement corrections, the possible inconsistency at the edge of two adjacent planes, and the need of large data formats.

Virtual Reference Station (VRS)

The Virtual Reference Station (VRS) method is currently the most popular NRTK method and was developed in the late 1990s (Vollath et al., 2000).

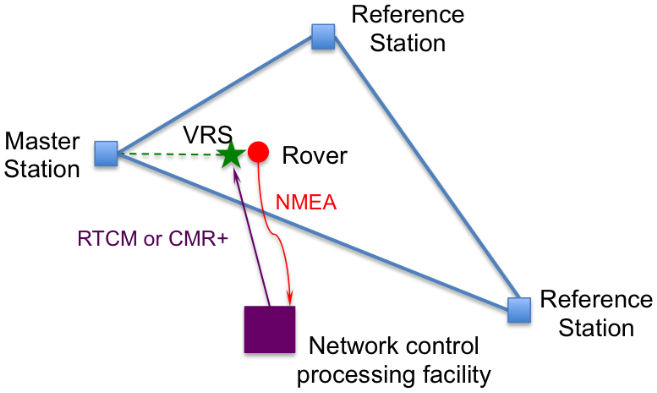


Figure 3 – Virtual Reference Station concept

The VRS method is a technique of creating synthetic observations for a non-physical, unoccupied and invisible reference station situated only few meters from the approximate location of the rover in order to improve the accuracy of the positioning solution achievable with conventional single-base RTK. VRS approach requires bi-directional communication. As depicted in Figure 3, the rover sends its approximate position to the network processing centerin National Marine Electronics Association (NMEA) format via a communication link (GSM, GPRS, or 3G).Once the location is received, the processing centermodels first the distance-dependent errors based on this location using a minimum three reference stations within the network and then interpolates the distance-dependent errors for the rover's approximate location. Further, the network center generates an optimal set of reference observations by shifting the measurements at a selected master reference station (e.g., the one closest to the rover) to a "virtual", non-existing station and applying the interpolated corrections. Finally, the network center sends raw modeled observations (or corrections) to the rover in RTCM or proprietary formats. If raw observations are sent, the correction process is carried out on the server-side, whereas if the corrections are sent, the rover has to apply them to its own observations. Finally, the rover computes position by doing standard RTK with own observations and VRS data.

A variation to the VRS algorithm is called Pseudo Reference Station (PRS). With this method, the virtual reference station is taken at a pre-selected grid point instead of the approximate position of the rover. Similar to VRS, the reference observations will also refer to a non-physical reference station.

The main benefitsof using VRS come from the fact that it does not required changes in the rover software being compatible with existing software, the rover processes data in the same way as conventional RTK, thus no complex computation on the rover side, and the network corrections are continuously optimized according to each rover position. However, the latter may also be seen as a drawback due to the fact that the rover is forced to re-initialize its position fix once it has travelled more than a certain distance from its initial position. In addition, VRS requires also duplex communication. The main drawback of VRS is the high computational burden to the network-processingcenter, due to the fact that VRS observations are computed separately for each user. Thus, there is a restriction on the number of simultaneously users according to the capacity of the processing center.

Master Auxiliary Concept (MAC)

The Master Auxiliary Concept (MAX) method is the only true multiple-station method and was proposed by Leica in 2001 (Euler et al., 2001).

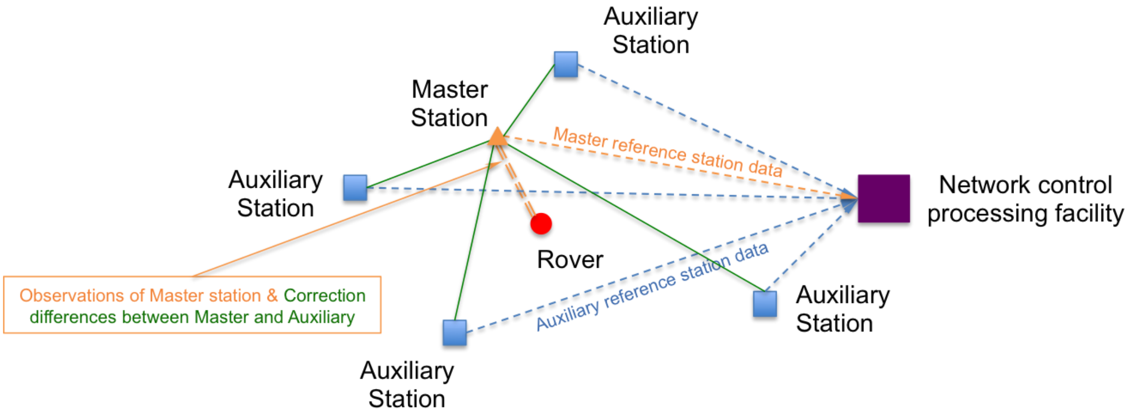


Figure 4 – Master Auxiliary Concept

In the MAC method, the network server sends full raw observations and coordinate information for a single reference station, the master station. For all other reference stations in the network (or sub-network) known as auxiliary stations, the network server transmits their ambiguity-leveled observations and coordinate differences (to the master station observations and coordinates). According to(Brown and Keenan, 2005), two reference stations are said to be on a common ambiguity level if the integer ambiguities for each phase range (satellite-receiver pair) have been removed (or adjusted) so that the integer ambiguities cancel when double differences (involving two receivers and two satellites) are formed during the network processing.

The reduction of the original raw reference station observations to a common ambiguity level is a fundamental requirement of MAC implementation. The ambiguity-leveled observations do not bring any benefit to single-base RTK processing because the modeling requirements are always the same. However, in case of multi-base RTK positioning we need to reinitialize the rover when switching from one reference to another and to account for integer ambiguities between the reference stations. The rover when receiving and utilizing the ambiguity-leveled observations of more than one reference station can avoid this, and the transition between the references is achieved without re-initialization.

The master station serves simply for data transmission purposes and plays no role in the computations of corrections. MAC gives the rover the flexibility to perform either a simple interpolation of the network corrections, like in FKP, or more rigorous calculation (e.g., multi-baseline RTK from the auxiliary stations) depending on its processing capabilities.

The major benefit of MAC is that it uses published standardized algorithms to generate and send network corrections. MAC concept complies with latest RTCM recommended standards for differential positioning. In addition, except of ambiguity resolution, no modeling or other computations are performed on the server side, thus, very low computational load on the network server. Furthermore, the rover can move freely and its location poses no restrictions on the kinematic applications.The user can utilize the master-auxiliary corrections (MAX) either in one-way (broadcast-MAX) or two-way (auto-MAX) communication modes.

4. TESTS AND RESULTS

Various static field tests were conducted in order to investigate the performance and suitability of NRTK positioning as an economic alternative to establish control points of a certain accuracy requirements.Table 1 gives a summary of these fields tests.

Table 1 – Summary of field experiments

DOY Session	251	258	259	265
Morning (07:00-11:00)	VRS		Single-base RTK	Post-processing
Afternoon (14:00-18:00)	VRS	Single-base RTK		10:00-14:00

Figure 5 – Equipment set-up (left) and testing mark (right)

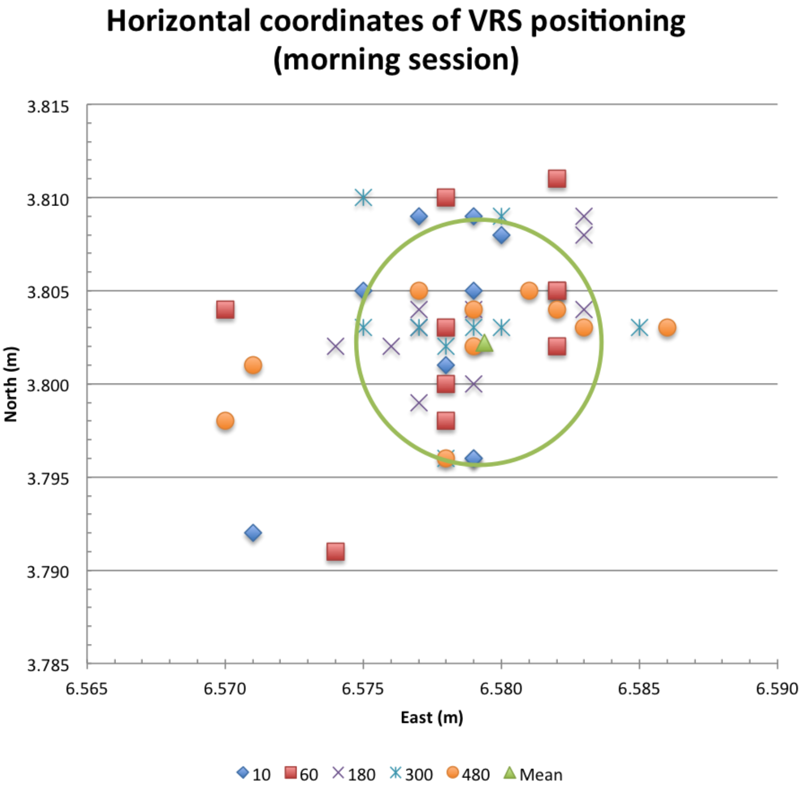
A number of 200 RTK coordinates were taken on the testing mark (**Figure**)in two observation sessions (one in the morning, one in the afternoon), covering five time intervals (10, 60, 180, 300, and 480 sec) and 10 occupations at each of the above intervals. This means that one RTK point occupation time is given by the total number of 1-second epochs logged over the given interval to produce an average coordinate for the mark.

The NRTK corrections were fetchedby connection to the ROMPOS service (ANCPI 2008). These corrections came in two different modes and formats: single-base mode (in RTCM 2.3 format) and VRS mode (in RTCM 3.1 format).

Precision test

Precision is a computed statistical quantity to describe the degree of repeatability between repeated measurements of the same quantity. It is a way to describe the quality of the data with respect to random errors. Precision is traditionally measured using the standard deviation and therefore is shown in the RMS error on the data collector screen (NGS, 2011).

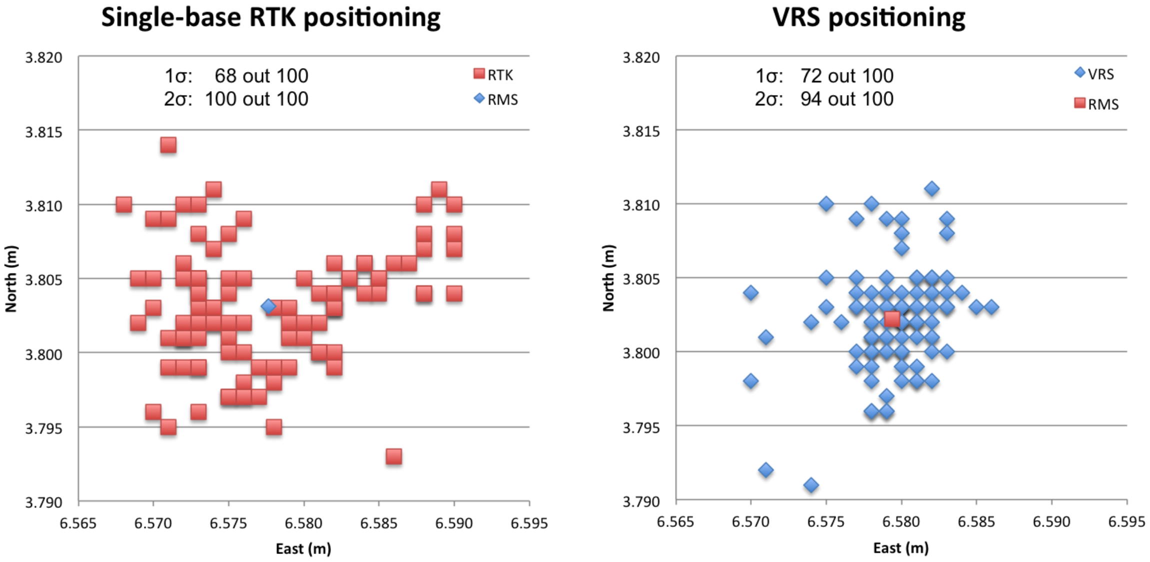
In GNSS positioning, a rover measurement shows precision of the observation and it is normally recorded in the data collector as the average position of many 1-second observations on the same mark. This should not be confused with the individual precision shown on the data collector screen for each 1-second log.



Precision circle (10 mm diam)
10 sec - 4 out of 10
60 sec - 6 out of 10
180 sec - 7 out of 10
300 sec - 7 out of 10
400 sec - 8 out of 10

Figure 6 – Precision of VRS measurement field testing

Figure 6 illustrates 50 NRTK coordinates taken on the testing mark during the morning session. 10 of the coordinates were for 10 seconds each, 10 coordinates were for 60 seconds each or 1 minute, 10 coordinates for 180 seconds each or 3 minutes, 10 coordinates for 300 seconds each or 5 minutes, and 10 coordinates for 480 seconds each or 8 minutes. It took about 3 hours to complete a full set. The green circle shown in the figure denotes a typical mark that has a 10 mm diameter circle and it is centered on the average coordinate of all 10 of the 480-second coordinates (the longest ones). This circle helps as to understand how observation time might affect the closeness of the groups. In addition, the table to the right shows that for 480-second (8 minutes) intervals, 8 out of 10 coordinates (of the orange dots) landed inside the circle. The light blue stars show 10 occupations of 300 seconds each and 7 out of 10 landed inside the mark circle. For the purple crosses (representing 180 seconds) 7 out of 10 landed inside the mark circle. For the 10 occupations of 60 seconds each (red squares), six landed inside the circle and last for the 10 occupations of 10 seconds each (blue diamonds) only four landed inside the circle. This is one example to show how less observation time per occupation influence directly the spread of the solution.



Single-base RTK positioning

VRS positioning

Horiz RMSE = 0.007 m
Vert RMSE = 0.011 m

Horiz RMSE = 0.005 m
Vert RMSE = 0.006 m

Figure 7 – Precision of horizontal coordinates

Figure depicts all horizontal coordinates obtained for the mark in both single-base RTK (left) and VRS positioning (right) for both observation sessions. It can be seen that VRS coordinates have a better precision comparing to single-base RTK. 72 out of 100 coordinates are within 1σ (68%) confidence interval. Although less precise, all RTK coordinates are within 2σ (95%) confidence interval. Moreover, it seems that most RTK coordinates are distributed along or vertical on the direction towards the CORS base station. However, further field tests on more marks are needed to generalize this observation. The overall root mean square error (RMSE) is given in the bottom of the two graphs.

Accuracy test

Accuracy is a computed statistical quantity to describe the degree of closeness of a measured value of a quantity to its “true” value. Although the accuracy accounts for all types of errors, it is particularly related to the influence of systematic errors. According to (NGS, 2011), the accuracy for real-time positioning is defined by the horizontal and/or vertical positioning error ellipse (or covariance matrix) at 2σ (95%) confidence level directly related to the base station as the representative of the datum. Typically, the alignment to the truth is done by some method of post-processing observations of the GNSS station constrained by CORS data.

To determine what is the accuracy for I053 mark, an independent 4-hour static occupation was logged and then submitted to OPUS (OPUS, 2013), which returned a solution for the mark with peak-to-peak errors that are shown in the yellow circle around the coordinate labeled as the center of accuracy. The OPUS solution in this case represents the truth check.

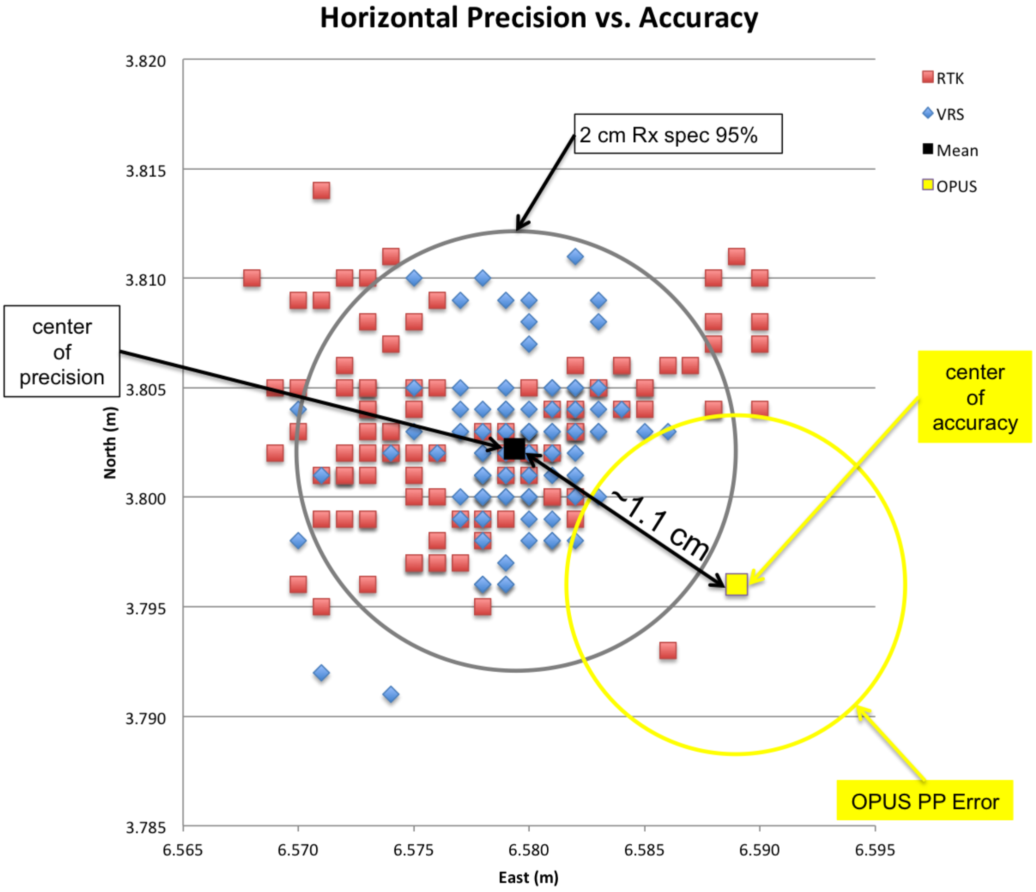


Figure 8 – Horizontal precision vs. accuracy

Figure shows that there is some bias between of the real-time positions with respect to the center of accuracy (the OPUS PP solution). Nevertheless, the difference from the precision (8 minute average) center and the accuracy center (truth) determined from OPUS was about 1.1 cm and fell within the 2 cm specification goal for the test. In addition, most of the RTK and VRS occupations appear to meet the receiver's performance accuracy specification at 95% confidence illustrated through the 2 cm gray circle. However, several occupations mainly from 60 second and 10 second intervals fell outside of the circle appearing to not meet the receiver specifications.

5. CONCLUSIONS

This study reports preliminary testing results of an investigation of the NRTK GNSS positioning from the user's point of view using ROMPOS service. Several static tests are carried out to analyze the performance of NRTK positioning regarding the precision, accuracy and occupation time. In addition, the study illustrates the benefit of averaging the observations over a window of 1-3 minutes and re-occupying the points after 10-30 minutes later. The results demonstrate that NRTK is superior to single-base RTK and may be an economic alternative to establish control points of a certain accuracy requirements. However, the authors recommend to field test NRTK corrections to see if both precision and accuracy are within the user's project expected tolerance. Moreover, if NRTK positioning is used for survey control, the user is advised to observe for 8 minutes or perhaps even longer, down to

10 minutes to increase precision of the positioning solution. Nevertheless, the occupation time can be reduced to 2-3 minutes but the user is recommended to use multiple occupations for the same mark. The occupations should be separated by a time period to allow for constellation geometry change.

6. REFERENCES

[1] ANCPI (2008). "ROMPOS - SistemulRomânesc de Determinare a Poziţiei", on-line. Available at: http://www.rompos.ro/(Accessed November 10, 2013).

[2] Brown, N., Keenan, R. (2005). "Take it to the MAX! - An introduction to the philosophy behind Leica Geosystems' SpiderNET revolutionary Network RTK software and algorithms". White paper, Leica Geosystems, Switzerland, 2005.

[3] Euler, H. J., Keenan, C.R., Zebhause, B.E. (2001). "Study of a Simplified Approach in Utilizing Information from Permanent Reference Station Arrays", Proceedings of the 14th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 2001), Salt Lake City, UT, September 2001, pp. 379-391.

[4] Landau, H., Vollath, U., Chen, X. (2002). "Virtual Reference Station Systems." Journal of Global Positioning Systems, Vol. 1, no. 2, pp. 137-143.

[5] NGS (2011). "Guidelines for Real Time GNSS Networks", on-line, National Oceanic and Atmospheric Administration, National Geodetic Survey, 2011. Available: http://www.ngs.noaa.gov/PUBS_LIB/NGS.RTN.Public.v2.0.pdf (Accessed November 10, 2013).

[6] OPUS (2013). "Online Positioning User Service", Available at: http://www.ngs.noaa.gov/OPUS/ (Accessed November 10, 2013).

[7] Teunissen, P., Odijk, D.J.G & Zhang, B. (2010). "Results of CORS Network Based PPP with Integer Ambiguity Resolution", Journal of Aeronautics, Astronautics and Aviation, Series A, Vol. 42, No. 4, pp. 223-230.

[8] Vollath, U., Buecherl, A., Landau, H., Pagels, C., Wagner, B. (2000). "Multi-Base RTK Positioning Using Virtual Reference Stations", Proceedings of the 13th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 2000), Salt Lake City, UT, September 2000, pp. 123-131.

[9] Wübenna G., Bagge A., Seeber G., Volker B., Hankemeier P. (1996). "Reducing Distance Dependent Errors for Real Time Precise DGPS Applications by Establishing Reference Station Networks", Proceedings of the Institute of Navigation, National GPS 1996 Kansas, 17-20 September, Vol. 2, 1845-1852.

[10] Wübbena, G., Bagge, A., Schmitz, M. (2001). "Network-Based Techniques for RTK Applications", Proceedings the GPS JIN 2001 Symposium, GPS Society, Japan Institute of Navigation, Tokyo, Japan, November 14-16, 2001. Available: http://www.geopp.de/download/gpsjin01_p.pdf (Accessed November 10, 2013)

[11] Wübbena, G., Bagge, A. (2006). "RTCM Message Type 59 - FKP for transmission of FKP", Version 1.1, Geo++ GmbH White Paper Nr. 2006.01, 17.7.2009, Available: http://www.geopp.de/download/geopprtcmfkp59- 1.1.pdf (Accessed November 10, 2013)